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Ultra faint dwarfs: probing early cosmic star formation

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ABSTRACT

We investigate the nature of the newly discovered Ultra Faint dwarf spheroidal galaxies (UF dSphs) in a general cosmological context simultaneously accounting for various 'classical' dSphs and Milky Way properties including their metallicity distribution function (MDF). To this aim, we extend the merger tree approach previously developed to include the presence of star-forming minihaloes, and a heuristic prescription for radiative feedback. The model successfully reproduces both the observed [Fe/H]–luminosity relation and the mean MDF of UFs. In this picture, UFs are the oldest, most dark matter-dominated ($M/L > 100$) dSphs with a total mass $M = 10^{7-8}\,\mathrm{M}_{\odot}$; they are leftovers of H_2-cooling minihaloes formed at $z > 8.5$, that is before reionization. Their MDF is broader (because of a more prolonged star formation) and shifted towards lower [Fe/H] (as a result of a lower gas metallicity at the time of formation) than that of classical dSphs. These systems are very ineffectively star-forming, turning into stars by $z = 0$ only <3 per cent of the potentially available baryons. We provide a useful fit for the star formation efficiency of dSphs.

Key words: stars: formation – stars: population II – supernovae: general – galaxies: evolution – cosmology: theory – galaxies: stellar content.

1 BACKGROUND

The dwarf spheroidal galaxy (dSph) population observed in the Milky Way (MW) system provides crucial insights into cosmic structure formation. Nevertheless, the origin and evolution of dSphs has so far escaped any comprehensive theoretical interpretation and the picture is now further complicated by the discovery of a new class of dwarf satellite galaxies: the Ultra Faint dSphs (UFs).

The UFs are the least luminous galaxies known, with a total luminosity $L \approx 10^{3-5}\,\mathrm{L}_{\odot}$; spectroscopic follow-up has revealed that they are highly dark matter dominated systems $M/L > 100$ (Simon & Geha 2007; Geha et al. 2008). Their average iron-abundance is $\langle[\mathrm{Fe/H}]\rangle < -2$ (Kirby et al. 2008) i.e. they represent the most metal-poor stellar systems ever known; although more data are required to solidly constrain stellar populations, at the moment *all* of them appear to be dominated by an old stellar population (Walsh, Willman & Jerjen 2009), with the only exception of LeoT (de Jong et al. 2008). In addition, UFs are relatively common in the MW system, representing more than 50 per cent of the total number of dSph companions discovered so far ($N \approx 20$); hence, they are not peculiar objects. When and how did UFs form?

The [Fe/H]–luminosity relation derived for UFs (Kirby et al. 2008) constitutes an extension towards lower metallicity of that of 'classical' dSphs ($L > 10^5\,\mathrm{L}_{\odot}$). Such a continuous trend seems to exclude that processes (e.g. tidal stripping) different from those shaping the relation for classical dSphs become dominant in these objects. However, while dSphs and UFs together span more than four orders of magnitude in luminosity, their total mass is roughly the same $M \approx 10^7\,\mathrm{M}_{\odot}$ within the innermost 300 pc (Li et al. 2008; Strigari et al. 2008). Why is then star formation so inefficient in UF satellites?

The puzzle is made even more intriguing by the observation of metal-poor stars in UFs (Kirby et al. 2008) which have revealed the existence of a $[\mathrm{Fe/H}] < -3$ stellar population, in contrast with the classical dSphs which are lacking extremely iron-poor stars (Helmi et al. 2006). Does this reflect a different origin of UF and classical dSphs? In this Letter, we extend previous works [Salvadori, Schneider & Ferrara 2007 (SSF07); Salvadori, Ferrara & Schneider 2008 (SFS08)] to investigate the origin of UF galaxies in a cosmological context.

2 MODEL FEATURES

In this section, we will briefly describe the basic features of the model implemented in the code GAMETE (GAlaxy MErger Tree & Evolution) which allows us to reconstruct the stellar population history and the chemical enrichment of the MW along its hierarchical merger tree, following at the same time the formation and evolution

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of dSph satellites.[1] In such a model, dSphs form out of the MW environment, or Galactic medium (GM), whose metal enrichment strongly depends on the star formation (SF) history and mechanical feedback along the hierarchical tree. The model successfully reproduces the global properties of the MW and the metallicity distribution function (MDF) of Galactic halo stars, along with the observational properties of prototype dSphs, as for example Sculptor (SFS08).

The merger history of the MW is reconstructed starting from $z = 20$ via a Monte Carlo algorithm based on the extended Press–Schechter theory and by adopting a binary scheme with accretion mass (Volonteri, Haardt & Madau 2003). The evolution of gas and stars is then followed along the hierarchy with the following hypotheses: (a) stars can only form in haloes of mass $M_{\rm h} > M_{\rm sf}(z)$; the evolution of $M_{\rm sf}(z)$ will be discussed in the next section; (b) in each halo, the SF rate is proportional to the mass of cold gas whose gradual accretion is described by a numerically calibrated infall rate (Kereš et al. 2005); (c) according to the so-called critical metallicity scenario (Schneider et al. 2002, 2006), low-mass stars with a Larson initial mass function form when the gas metallicity $Z \geq Z_{\rm cr} = 10^{-5\pm1}\,{\rm Z}_{\odot}$; below $Z_{\rm cr}$ massive Population III stars form with a reference mass $m_{\rm PopIII} = 200\,{\rm M}_{\odot}$. The chemical enrichment of the gas is followed by taking into account mass-dependent stellar evolutionary time-scales (Lanfranchi & Matteucci 2007). We follow the chemical evolution of gas both in proto-Galactic haloes and in the GM by including a physically based description of the mechanical feedback due to supernova (SN) energy deposition (see SFS08 for details). Metals and gas are assumed to be instantaneously and homogeneously mixed with the gas (implications discussed in SFS08). The code is calibrated by simultaneously reproducing the global properties of the MW (stellar/gas mass and metallicity) and the MDF of metal poor stars observed by Beers & Christlieb (private communication) in the Galactic halo (for details see SSF07).

Dwarf spheroidal candidates are selected among star-forming haloes ($M_{\rm h} > M_{\rm sf}$) which are likely to become satellites, i.e. those corresponding to density fluctuations $<2\sigma$.[2] Such a dynamical argument is based on *N*-body cosmological simulations by Diemand, Madau & Moore (2005). Therefore, at each redshift, we select dSph candidates from the merger tree among haloes with $M_{\rm sf} < M_{\rm h} < M_{2\sigma}$; we then follow the isolated evolution (no further merging or accretion events) of 'virtual' haloes with the same initial conditions (dark matter/gas/stellar content, metallicity). Through this method, we build a statistically significant dSph sample; however, it prevents us from making specific predictions on the actual number of dSph satellites.

2.1 Feedback and star formation

Radiative feedback processes are crucial to determine the minimum mass, $M_{\rm sf}$, and efficiency, f_*, for SF. The redshift evolution of the minimum mass of star-forming haloes, $M_{\rm sf}$, is determined by two distinct radiative feedback processes. The first one has to do with the increase of the Jeans mass in progressively ionized cosmic regions;

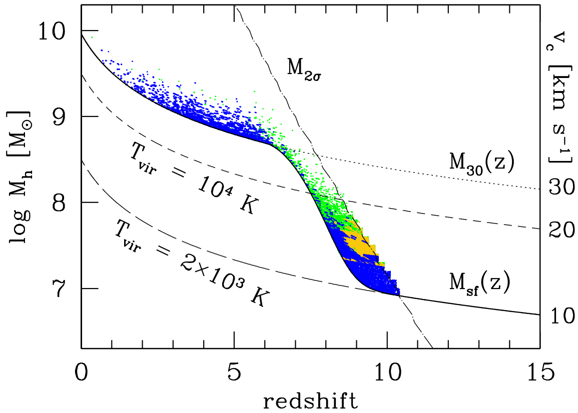

Figure 1. Dark matter halo mass and circular velocity of selected dSph candidates as a function of their formation redshift z (points) for 10 realizations of the hierarchical merger tree. Different colours show the baryonic fraction $f_{\rm b}$ at the formation epoch with respect to the cosmic value $f_{\rm c} = 0.156$: $f_{\rm b}/f_{\rm c} > 0.5$ (blue), $0.1 < f_{\rm b}/f_{\rm c} < 0.5$ (green), $f_{\rm b}/f_{\rm c} < 0.1$ (yellow). The lines show the evolution of $M_{\rm sf}(z)$ (solid), $M_{30}(z)$ (dotted), the halo mass corresponding to 2σ peaks (dotted-long dashed), $T_{\rm vir} = 10^4$ K (short dashed line) and $T_{\rm vir} = 2 \times 10^3$ K (long dashed line).

as a result, the infall of gas in haloes below a given circular velocity, $v_{\rm c}^*$, is quenched and such objects are gas-starved. The evolution of $v_{\rm c}^*$ (z) depends on the details of the reionization history (Gnedin 2000; Schneider et al. 2008); we adopt the typical value $v_{\rm c}^* = 30$ km s^{-1} after the end of reionization $z_{\rm rei} = 6$, i.e. we assume $M_{\rm sf}(z) = M_{30}(z)$ when $z < 6$. Before reionization, a second type of feedback, related to the photodissociation of H_2 molecules by the Lyman–Werner (LW) background photons, becomes important. As this species is the only available coolant for 'minihaloes' ($T_{\rm vir} < 10^4$ K), SF is suppressed in these objects to an extent which depends on the intensity of the UV background (Haiman, Rees & Loeb 1996; Ciardi, Ferrara & Abel 2000; Kitayama et al. 2000; Machacek, Bryan & Abel 2001). According to Dijkstra et al. (2004) at $z \approx 10$ objects with $v_{\rm c} \geq 10$ km s^{-1} ($T_{\rm vir} \approx 2000$ K) can self-shield and collapse; therefore we use this value as the minimum absolute threshold for SF. During reionization ($6 < z < 9$), the interplay between these two feedback types is quite complicated and no consensus is found on the evolution of $M_{\rm sf}(z)$ (see for example fig. 25 of Ciardi & Ferrara 2005). Instead of modelling in detail the build-up of LW and ionizing UV backgrounds, we interpolate between the low- and high-redshift behaviours and use an heuristic form for $M_{\rm sf}(z)$ which leads to the suppression of SF in gradually more massive objects (Fig. 1). Such parametrization of $M_{\rm sf}(z)$ allows to correctly reproduce the observed iron–luminosity relation of dSphs (Fig. 2).[3] Fig. 1 also shows the halo masses of selected dSph candidates along with their initial baryonic fraction, $f_{\rm b}$, with respect to the cosmic value $f_{\rm c} = \Omega_{\rm b}/\Omega_{\rm M} = 0.156$. We classify dSphs according to their initial baryonic content as gas-rich, $f_{\rm b}/f_{\rm c} > 0.5$, intermediate, $0.1 < f_{\rm b}/f_{\rm c} < 0.5$, and gas-poor, $f_{\rm b}/f_{\rm c} < 0.1$, systems.

A second important feature of the model is that we consider a mass-dependent SF efficiency. In minihalos, in fact, the ineffective cooling by H_2 molecules limits the amount of gas than can be transformed into stars. Several authors (Madau, Ferrara & Rees 2001; Ricotti & Gnedin 2005; Okamoto, Gao & Theuns 2008)

[1] We adopt a Λ cold dark matter (ΛCDM) cosmological model with $h = 0.73$, $\Omega_{\rm m} = 0.24$, $\Omega_\Lambda = 0.72$, $\Omega_{\rm b}h^2 = 0.02$, $n = 0.95$ and $\sigma_8 = 0.74$, consistent with *Wilkinson Microwave Anisotropy Probe* 5 (*WMAP*5) data (Spergel et al. 2007); we assume the fit to the power spectrum proposed by Bardeen et al. (1986) and modified by Sugiyama (1995).

[2] The quantity $\sigma(M, z)$ represents the linear rms density fluctuation smoothed with a top-hat filter of mass M at redshift z.

[3] The total luminosity value is derived from the stellar mass content as $L = M_* \times (M/L)_*^{-1}$ by assuming $(M/L)_* = 1$.

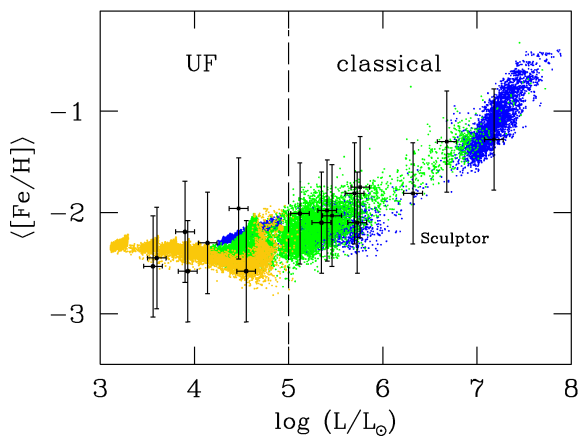

Figure 2. Total luminosity of selected dSph candidates as a function of their average iron abundance (points) for 10 realizations of the hierarchical merger tree. As in Fig. 1, different colours show the baryonic fraction at the formation epoch with respect to the cosmic value. The points with error bars are observational data from Kirby et al. (2008).

agree that in these systems the SF efficiency decreases $\propto T_{\rm vir}^3$. A suitable form is then

$$\epsilon \propto \epsilon_* \left[1 + \left(\frac{T_{\rm vir}}{2 \times 10^4 \rm K}\right)^3\right]^{-1}, \quad (1)$$

where ϵ_* is the value determined by matching the global properties of the MW.

3 RESULTS

The first test of the model is a comparison of the observed metallicity–luminosity relation with our predictions; the results are reported in Fig. 2. The overall agreement is satisfactory, and the increasing trend of metallicity with luminosity well reproduced. The faint end of the relation, $L < 10^6\,{\rm L_\odot}$, is pre-dominantly populated by minihaloes; above that luminosity H-cooling haloes dominate. The low-L segregation of minihaloes naturally arises from their low masses and it is further extended towards very faint luminosities, $L < 10^4\,{\rm L_\odot}$, by the reduced SF efficiency and, most importantly, by their low initial baryonic fraction $f_{\rm b}/f_{\rm c} < 0.1$. Being UFs defined as systems with $L < 10^5\,{\rm L_\odot}$, we conclude that all UFs are minihaloes but there are minihaloes that are not UFs.

We have just pointed out that the initial baryonic fraction is a key factor in dSph galaxy evolution. What sets such initial value? Gas-rich systems are distributed through the entire mass ($M_{\rm h} = 10^{7-10}\,{\rm M_\odot}$) and formation redshift ($z = 2$–10) ranges of selected dSph candidates (Fig. 1). These dSphs are the present-day counterpart of pre-dominantly newly virialized objects accreting gas from the GM. Intermediate systems ($0.1 < f_{\rm b}/f_{\rm c} < 0.5$) originate from mixed merging of star-forming and starless progenitors; they are typically more massive than gas-rich haloes and form at lower redshifts. Their smaller baryonic content is the result of shock-heating of the infalling gas during major merging events (Cox et al. 2004) which stops accretion. Finally, gas-poor systems formed by merging of *recently* virialized, $M_{\rm h} > M_{\rm sf}$ progenitors. Since most of the diffuse gas is still accreting, shock heating quenches the infall early on. Note that a low baryonic content might also result from shock-stripping of the gas due to winds outflowing from nearby galaxies (Scannapieco, Ferrara & Broadhurst 2000).

The faintest UFs are found to be gas-poor systems; this fact has two important implications. First, being the SN rate depressed in these systems by the scarce availability of gas, mechanical feedback has negligible effects, and they evolve as a closed-box. As essentially all metals are retained they have a relatively high Fe-abundance which is seen as an almost inverted Fe–L relation below $L = 10^{4.5}\,{\rm L_\odot}$. Secondly, UFs have extremely large $M/L > 100$ ratios, and the faintest ones among them reach such extreme values as $M/L \approx 10^4$.

To get more insight in the nature of UFs, it is instructive to analyse their stellar MDF. In Fig. 3 (left-hand panel), we show the MDF averaged over all UF candidates in 10 realizations of the merger tree, along with the available data (Kirby et al. 2008). The shape of the distribution is relatively broad extending from [Fe/H] ≈ -4 to ≈ -1, in good agreement with observations. This is notably different from the Sculptor MDF shown in the right-hand panel of the same figure. SN feedback in Sculptor is much stronger than in UFs, as explained above; SF activity is then terminated shortly after 100 Myr (see fig. 3 of SFS08) whereas UFs can continue to quietly form stars up to 1 Gyr from their birth. These physical differences are reflected in the wider UF MDF. In our model, Sculptor-like dSphs[4] are associated with gas-rich, H-cooling haloes, with $M_{\rm h} \approx 10^8\,{\rm M_\odot}$, virializing at $z \approx 7.5$, in agreement with the findings in SFS08. However, in contrast with that study, we now predict a small tail of [Fe/H] < -3 stars. These are relics of the rare SF episodes occurred in some progenitor minihaloes (which were not considered in SFS08) at $z > 7.5$. Therefore, such a small number of very iron-poor stars in classical dSphs are expected to be characterized by the same abundance pattern of [Fe/H] < -3 stars in UFs. The rest of the MDF, on the contrary, is built after the stellar population bulk assembling at lower redshifts. A striking difference between the two distributions in Fig. 3 is the larger fraction ($\approx$25 per cent) of very metal poor stars ([Fe/H] < -3) present in the UF MDF. The interpretation of this result is clear: as UFs form earlier the metallicity of the GM gas out of which they virialize is correspondingly lower but still high enough that low-mass stars can be produced according to the critical metallicity criterion. In principle, then, UFs are potentially powerful benchmarks to validate this criterion, which would exclude the presence of stars of *total* metallicity below $Z_{\rm cr}$, here fixed at $Z_{\rm cr} = 10^{-3.8}\,{\rm Z_\odot}$ (see SFS08 for details).

4 DISCUSSION

UFs are the oldest and most dark matter ($M/L > 100$) dominated dSphs in the MW system with a total mass $M = 10^{7-8}\,{\rm M_\odot}$ and $L = 10^{3-5}\,{\rm L_\odot}$; they are found to be leftovers of H_2-cooling minihaloes formed at $z > 8.5$, that is before reionization. Their MDF is broader (because of their more prolonged SF) and shifted towards lower [Fe/H] (as a result of a lower GM metallicity at the time of formation) with respect to classical dSphs.

The SF in the faintest UFs is depressed by two factors: the limited availability of cold, star-forming gas due to ineffective H_2 cooling, and their specific formation mechanism resulting in gas-starved systems. The mass of stars formed at $z = 0$ normalized to the cosmic baryon content associated with a halo of mass $M_{\rm h}$, $\mathcal{F} = M_*/f_{\rm c} M_{\rm h}$ is shown in Fig. 4 as a function of $M_{\rm h}$. A handy fit to the curve is given by

$$\mathcal{F} = \exp(a + bx + cx^2), \quad (2)$$

[4] $L \approx 10^{6.2}\,{\rm L_\odot}$, $\langle$[Fe/H]$\rangle \approx -1.8$, see also Fig. 2.

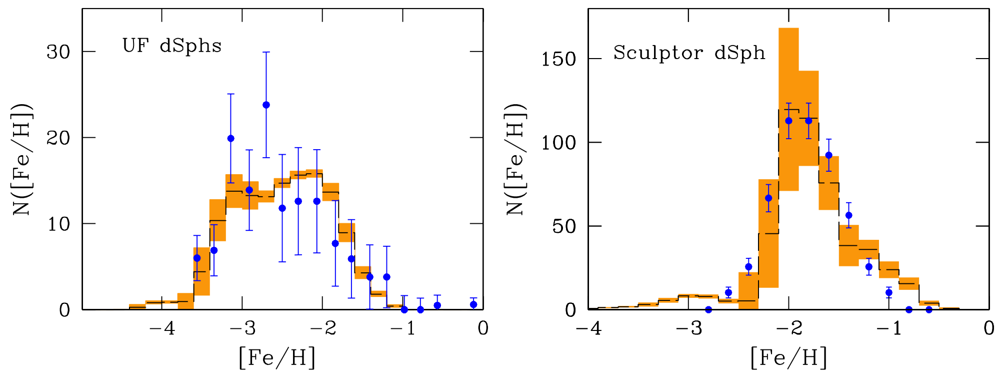

Figure 3. Left-hand panel: comparison between the MDF of UFs observed by Kirby et al. (2008) (points) and the simulated one (histogram). Error bars are the rms dispersion in [Fe/H]. The histogram is the averaged MDF over all UFs candidates ($L < 10^5\,L_\odot$) in 10 realizations of the merger tree. The shaded area represents the 1σ scatter among different realizations. Right-hand panel: comparison between the Sculptor MDF observed by Helmi et al. (2006) (points) and the simulated one (histogram). Error bars are the Poissonian errors. The histogram is the averaged MDF over all the Sculptor-like dSph candidates ($10^6\,L_\odot < L < 10^{6.5}\,L_\odot$) in 10 realizations of the merger tree. The shaded area represents the $\pm1\sigma$ Poissonian error.

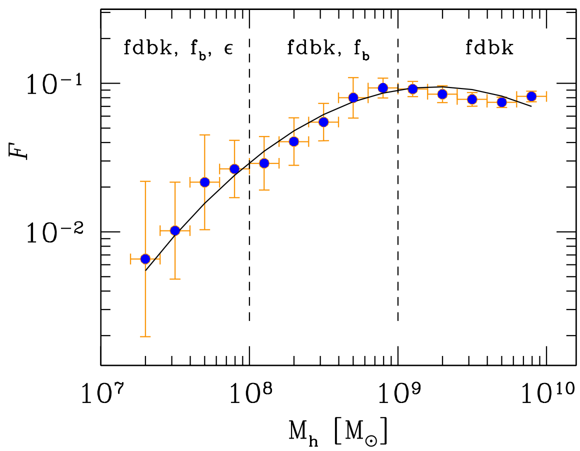

Figure 4. Fraction $\mathcal{F} = M_*/f_c M_h$ of the potentially available cosmic baryon content turned into stars as a function of M_h. The points are the average over all dSph candidates in 10 realizations of the merger tree. Error bars show the $\pm1\sigma$ dispersion among different dSphs. The solid line is the handy fit.

where $a = -66$, $b = 5.97$, $c = -0.14$ and $x = ln(M_h/M_\odot)$. By inspecting that figure the interplay between different factors affecting SF can be readily understood. Haloes above $10^9\,M_\odot$ convert about 10 per cent of their potentially available $f_c M_h$ baryonic mass into stars; this value is solely determined by mechanical feedback. In haloes with $10^8 - 10^9\,M_\odot$, gas infall starts to be quenched by shock heating during formation by mergers, with SN feedback playing a subdominant role. Therefore, $\mathcal{F}$ drops by about a factor of 3 in this range. Finally, minihaloes $M_h < 10^8\,M_\odot$ are affected by an additional suppression factor related to their decreasing SF efficiency (equation 1) due to radiative feedback acting on the H_2 chemical network. The larger $\mathcal{F}$ scatter towards low M_h is hence due to the increasing number of physical processes influencing SF.

The recent work of Madau et al. (2008) attempts to determine $\mathcal{F}$ for minihaloes by matching the luminosity function of MW satellites in the Sloan Digital Sky Survey (SDSS) under the assumption that the formation of these systems stopped at $z_{rei} = 11$ due to reionization photoheating. They find that $\mathcal{F} = (0, 0.0025, 0.02)$ for haloes with a total mass $M_h = [<3.5 \times 10^7\,M_\odot, (3.5 - 7) \times 10^7\,M_\odot, >7 \times 10^7\,M_\odot]$. In the same range of masses, we find slightly higher $\mathcal{F}$ values (Fig. 4); this difference is likely due to the assumption made here that $z_{rei} = 6$. It is however unclear what is the effect of an early, $z > 11$, formation on the median and shape of the minihaloes/UFs MDF; on the other hand, our model cannot predict if the higher $\mathcal{F}$ produces an excess of visible MW satellites. Clearly, a more comprehensive study is required to answer these questions.

Our conclusions support the ‘primordial scenario’ for the origin of dSphs proposed by Bovill & Ricotti (2008). In such a scenario, feedback effects of the type discussed here represent fundamental evolutionary ingredients. The picture is strengthened by the successful simultaneous match of the Fe–L relation and the MDF of UFs. Our model reproduces at the same time also the observed MDF of both the MW and of a prototypical classical dSph as Sculptor.

The sceptic might wonder about the possible role of tidal stripping. In our picture, UFs are, among all dSphs, those associated with the highest σ fluctuations ($\sim 2\sigma$) forming at the earliest possible epochs (Fig. 1). According to N-body cosmological simulations (Diemand et al. 2005), this implies that UFs are most probably found at small Galactocentric radii, as indeed deduced from observations; such data however must be interpreted with care as it might be biased due to the magnitude limit of the SDSS. The proximity to the MW may cause gas/stellar loss by tidal stripping from these satellites (Mayer et al. 2007). However, it seems unlikely that UF can be the stripped remnant of classical dSph as the scaling of the luminosity–velocity dispersion with luminosity would be too steep to explain the observed trend (Peñarrubia, Navarro & McConnachie 2008). The success of our model also lends support to the conclusion that tidal stripping plays at most a minor role.

A final caveat concerns the adopted heuristic assumption for $M_{sf}(z)$. Physically $M_{sf}(z)$ is tightly related to the reionization history of the MW environment. Although we have not attempted to model in detail the radiative feedback processes determining the evolution of such quantity, which we defer to further study, it is conceivable that the grow of the LW background intensity will suppress the cooling and SF ability of progressively more massive minihaloes. Guided by this general argument, we have then chosen an heuristic form of $M_{sf}(z)$ which suitably accounts for this physical process as required by the data. A more physical interpretation of its shape derived from a detailed modelling of the LW background intensity growth during reionization is nevertheless necessary; it may well unfold the complicated physics behind radiative feedback.

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REFERENCES

Bardeen J. M., Bond J. R., Kaiser N., Szalay A. S., 1986, ApJ, 304, 15
Bovill M. S., Ricotti M., 2008, preprint (arXiv:0806.2340)
Ciardi B., Ferrara A., 2005, Space Sci. Rev., 116, 625
Ciardi B., Ferrara A., Abel T., 2000, ApJ, 533, 594
Cox T. J., Primack J., Jonsson P., Sommerville R. S., 2004, ApJ, 607, L87
de Jong J. T. A. et al., 2008, ApJ, 680, 1112
Diemand J., Madau P., Moore B., 2005, MNRAS, 364, 367
Dijkstra M., Haiman Z., Rees M. J., Weinberg D. H., 2004, ApJ, 601, 666
Geha M., Willman B., Simon J. D., Strigari L. E., Kirby E. N., Law D. R., Strader J., 2008, ApJ, in press (arXiv:0809.2781)
Gnedin N. Y., 2000, ApJ, 542, 535
Haiman Z., Rees M. J., Loeb A., 1996, ApJ, 467, 522
Helmi A. et al., 2006, ApJ, 651, L121
Kereš D., Katz N., Weinberg D. H., Davé R., 2005, MNRAS, 363, 2
Kirby E. N., Simon J. D., Geha M., Guhathakurta P., Frebel A., 2008, ApJ, 685, L43
Kitayama T., Tajiri Y., Umemura M., Susa H., Ikeuci S., 2000, MNRAS, 315, 1
Lanfranchi G., Matteucci F., 2007, A&A, 468, 927
Li Y.-S., Helmi A., De Lucia G., Felix S., 2008, preprint (arXiv:0810.1297)
Machacek M. E., Bryan G., Abel T., 2001, ApJ, 548, 509
Madau P., Ferrara A., Rees M. J., 2001, ApJ, 555, 92
Madau P., Kuhlen M., Diemand J., Moore B., Zemp M., Potter D., Stadel J., 2008, ApJ, 689, L41
Meyer L., Kazantzidis S., Mastropietro C., Wadsley J., 2007, Nat, 445, 738
Okamoto T., Gao L., Theuns T., 2008, MNRAS, 390, 920
Peñarrubia J., Navarro J. F., McConnachie A. W., 2008, ApJ, 673, 226
Ricotti M., Gnedin N. Y., 2005, ApJ, 629, 259
Salvadori S., Schneider R., Ferrara A., 2007, MNRAS, 381, 647, (SSF07)
Salvadori S., Ferrara A., Schneider R., 2008, MNRAS, 386, 348, (SFS08)
Scannapieco E., Ferrara A., Broadhurst T., 2000, ApJ, 536, L11
Schneider R., Ferrara A., Natarajan P., Omukai K., 2002, ApJ, 571, 30
Schneider R., Omukai K., Inoue A. K., Ferrara A., 2006, MNRAS, 369, 1437
Schneider R., Salvaterra R., Choudhury T. R., Ferrara A., Burigana C., Popa L. A., 2008, MNRAS, 384, 1525
Simon J. D., Geha M., 2007, ApJ, 670, 313
Spergel D. N. et al., 2007, ApJS, 170, 377
Strigari L. E., Bullock J. S., Kaplinghat M., Simon J. D., Geha M., Willman B., Walker M. G., 2008, Nat, 454, 1096
Sugiyama N., 1995, ApJ, 100, 281
Volonteri M., Haardt F., Madau P., 2003, ApJ, 582, 559
Walsh S., Willman B., Helmut J., 2009, AJ, 137, 450

[5] www.arcetri.astro.it/science/cosmology/index.html

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